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Charging of Spinning Spacecraft

A. G. RUBIN
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It has become possible to calculate the effects of spin rate on charging only since the advent of the NASCAP three-dimensional computer simulation code. These spin effects are surveyed here for the first time. There is not only a dramatic difference in potential distribution between a three-axis stabilized and a spinning satellite, but also the case of slow spin at 1 rpm is shown to constitute a distinct intermediate case, asymptotic to the rapid spin case but with appreciable voltage modulation around the spin equator.

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Preface

The NASCAP program was developed by Systems, Science and Software, Inc., under a joint Air Force - NASA/LeRC project. We are indebted to Dr. Gary Schnuelle of Systems, Science and Software Inc., for his assistance with the calculations reported here.

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Illustrations

Charging of Spinning Spacecraft

1. BACKGROUND OF THE SPACECRAFT CHARGING PROBLEM

In 1971, DeForest[1] found, by analysis of particle spectra, that the ATS-5 spacecraft was charged at times to potentials as high as 20 kilovolts. In this time period, spacecraft anomalies had been observed, that is, spacecraft had malfunctioned or ceased to operate. It has since become clear that spacecraft can charge to high potentials at times of magnetospheric substorms[2,3,4] which consist of injections of bubbles of hot, tenuous plasma into the magnetosphere from the magnetospheric tail. The substorm plasma enters the magnetosphere at geosynchronous orbit, at about 6 earth radii on the night side of the earth. At geosynchronous orbit, the background plasma density is of the order of 10^{-1} to 10 particles per cm^3 so that a spacecraft encountering a hot plasma flow will charge up. At lower altitudes, the cold, dense plasmasphere inhibits charging.

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1. DeForest, S.E. (1972) Spacecraft charging at synchronous orbit, J. Geophys. Res. 77:651.
2. Spacecraft Charging by Magnetospheric Plasmas (1976) A. Rosen, Editor. MIT Press, Cambridge, Massachusetts
3. Proceedings of the Spacecraft Charging Technology Conference (1977) C.P. Pike and R.R. Lovell, Editors, NASA TMX-75537, AFGL-TR-77-0051, AD A045459.
4. Spacecraft Charging Technology - 1978 (1979) NASA Conference Publication 2071, AFGL-TR-79-0082.

Previous calculations of spacecraft charging were carried out using a current balance model to find the floating potential at which the net current to a spacecraft at steady state is zero.[1] These calculations are zero dimensional; that is, current balance is calculated for a single point and materials properties are treated as being linear with current. For instance, backscattering and secondary emission are given as fractions of the incident current. Another method of calculation of spacecraft charging is the representation of the ambient plasma by a circuit model with the spacecraft surface treated as an assembly of capacitors and resistors.[5,6] The results reported here are obtained with a 3-D computer simulation program, called NASCAP,[7,8] which yields potentials on the satellite surface and in the surrounding space.

2. STRUCTURE OF THE NASCAP CODE

NASCAP is a 3-D code which computes spacecraft charging. The spacecraft is represented in a finite element manner in a gridded space. A typical mesh size is $16 \times 16 \times 32$. By embedding meshes of smaller spacing into meshes of larger spacing, it is possible to accommodate long booms. A rather faithful representation of a spacecraft is contained in the code, as seen in Figure 1, which is a four-grid model of the SCATHA spacecraft.

NASCAP contains specifications of the materials properties of 15 spacecraft materials such as aluminum, gold, teflon, and kapton, and thermal control paints. Properties such as secondary emission coefficients, backscattering, photoemission, electrical conductivity, thickness of dielectric layers, and dielectric constant are specified. A variety of environments may be specified for charging, such as beams, single or double Maxwellians, or measured distribution functions for both ions and electrons. NASCAP treats the charging of thin dielectric layers on the surface of

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5. Inouye, G. (1976) Spacecraft potentials in substorm environment, Spacecraft Charging by Magnetospheric Plasmas, A. Rosen, Editor, MIT Press, Cambridge, Massachusetts, p. 103.
6. Massaro, M.J., Green, T., and Ling, D. (1977) A charging model for three-axis stabilized spacecraft, Proceedings of the Spacecraft Charging Technology Conference, C.P. Pike and R.R. Lovell, Editors, NASA TMX-73537, AFGL-TR-0051, AD A045459, p. 237.
7. Katz, I., Parks, D.E., Wang, S., and Wilson, A. (1977) Dynamic modeling of spacecraft in a collisionless plasma, Proceedings of the Spacecraft Charging Technology Conference, C.P. Pike and R.R. Lovell, Editors, NASA TMS-73537, AFGL-TR-77-0051, AD A045459, p. 319.
8. Katz, I., Cassidy, J.J., Mandell, M.J., Schnuelle, G.W., Steen, P.G., and Roche, J.C. (1979) The capabilities of the NASA charging analyzer program, Spacecraft Changing Technology - 1978, NASA Conference Publication 2071, AFGL-TR-79-0082.

conductors, as well as charging of the main body of the spacecraft. Shadowing by sunlight and photoemission from obliquely illuminated areas are first calculated. The charge and potential distribution on the spacecraft and in the surrounding space is computed in a quasistatic method as a function of time.

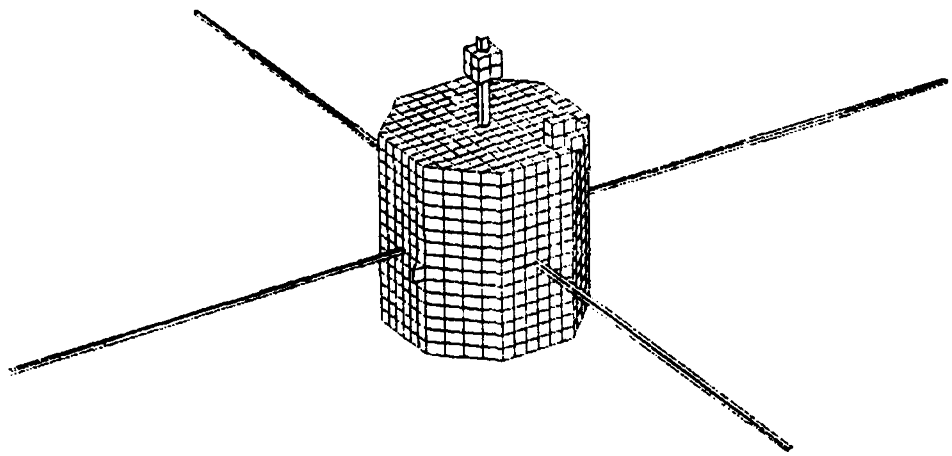

Figure 1. The SCATHA Satellite as Modeled by the NASCAP Code

In addition to a realistic three-dimensional representation of a spacecraft, NASCAP computes charging of a variety of simple objects, singly or in a combination. In order to study effects of spin and illumination, we chose a quasisphere as a test object, a 26-sided representation of a sphere, as shown in Figure 2.

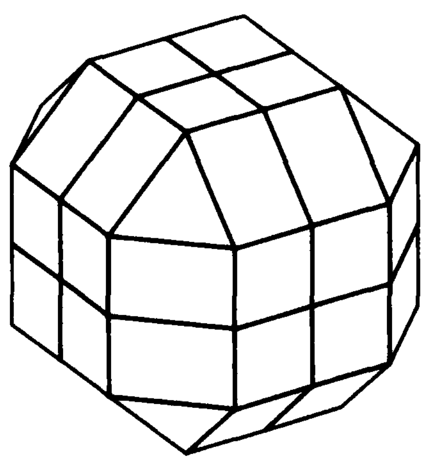

Figure 2. The Four-Mesh Diameter Quasisphere as Modeled by the NASCAP Code

3. RESULTS OF CHARGING OF THREE-AXIS STABILIZED SPACECRAFT

Charging of three-axis stabilized spacecraft by ambient substorm plasma has been studied by means of the NASCAP code for both the eclipse and sunlit cases.

Employing a simple geometrical structure, the quasisphere, which is the closest approach to a sphere possible in the NASCAP code, charging was calculated in environments characterizing quiet conditions, moderate and severe substorms.

Spin has no effect on potentials in an isotropic plasma environment. Differences between potentials in the stabilized and spin cases arise due to the fixed sunlight direction. The potential distribution about a stabilized spacecraft is the same as that about a spinning spacecraft in eclipse.

The potential distribution on a three-axis stabilized teflon-covered quasisphere in sunlight is shown in Figure 3 for a severe substorm environment characterized by a particle density of 10^6 per m^3, an electron temperature of 10 keV, and an ion temperature of 20 keV.

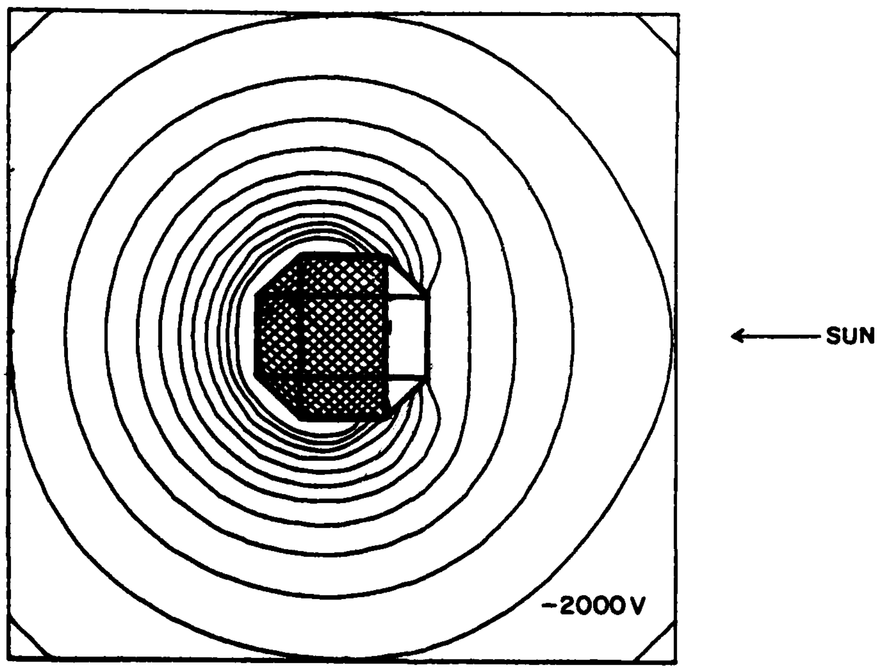

Figure 3. Steady-state Potential Distribution of a Three-axis Stabilized Teflon-covered Quasisphere in Sunlight During a Severe Substorm With Plasma Parameters T_e = 10 keV, T_i = 20 keV, $n_e = n_i = 10^6\ m^{-3}$. Equipotential contours are depicted in 500 V intervals

The potential is minimum on the sunlit side, and maximum on the shaded side, as might be expected. The potentials at the top and bottom are the same as the shaded side potentials. The spacecraft ground potential is highly negative and close to the shaded side potential.

The highest potential gradient is on the sunlit side between the teflon film and the underlying ground. There the gradient is 3.13 kV across 5 mils.

Mandell et al[9] have pointed out that multidimensional effects are important for a satellite in sunlight. The photosheath effects cannot be represented by a current balance model. The NASCAP code is used to calculate the photosheath. The present example makes use of more accurate values of electron induced secondary emission and more typical values of substorm plasma properties $n_e = n_i = 1$ per cm^3, $T_3 = 10$ keV, T_i 20 keV to obtain more realistic values of spacecraft potentials (see Figure 4). The physical mechanisms are unchanged, in that the photosheath produces a saddle point in the potential, which inhibits the outflow of low-energy photoelectrons. The net effect of the photosheath is to produce daylight charging, whose magnitude is somewhat less than 1/2 the potential of the shadowed side.

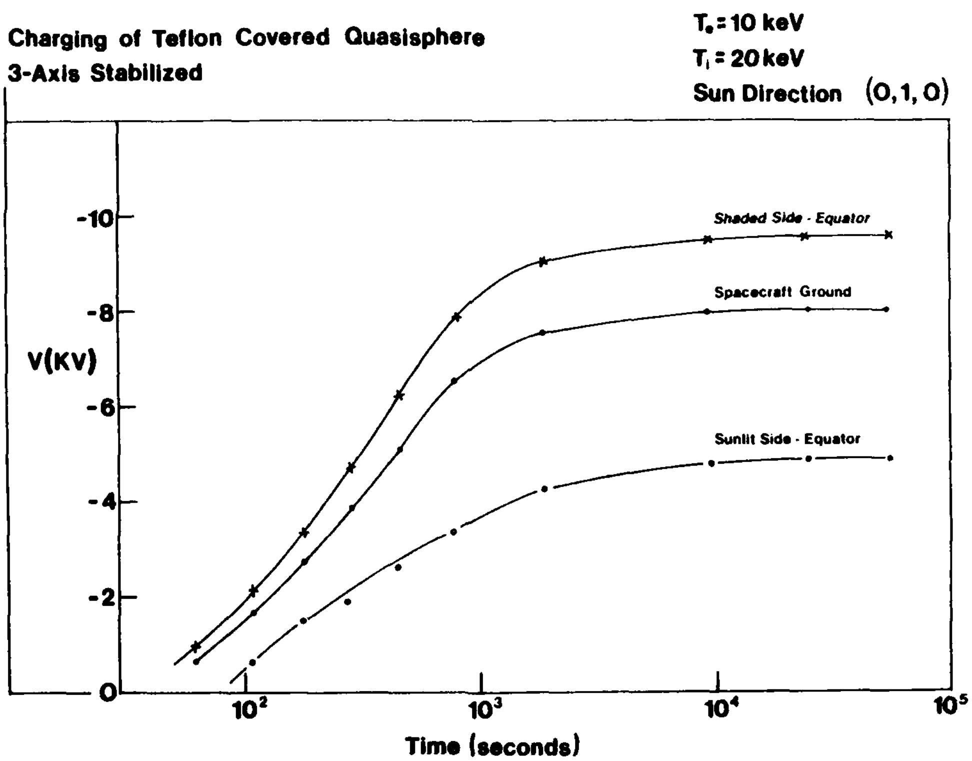

Figure 4. Time Development of Potentials on Non-spinning Teflon-covered Quasisphere in Sunlight

9. Mandell, M.J., Katz, I., Schnuelle, G., and Steen, P. (1978) The decrease in effective photocurrents due to saddle points in electrostatic potentials near differentially charged spacecraft, IEEE Trans. Nucl. Sci. NS-25(No. 6).

Daylight charging, a multidimensional effect, is present for all non-spinning spacecraft. Contrary to previous belief, sunlit surfaces can charge to kilovolts with ease.

4. CHARGING OF RAPIDLY SPINNING SPACECRAFT

The case of a rapidly spinning satellite is treated in the NASCAP code by using the average solar flux on the satellite, assuming uniform illumination at all angles of rotation. Figure 5 shows the resulting steady-state potentials on the teflon quasisphere. The potential has now dropped considerably; it is -1050 V at the equator of the quasisphere and -6250 V at the poles. The spacecraft ground potential is -1900 V. The largest differential voltage is no longer across the dielectric to ground, but between the spacecraft poles and equator. The highest potential gradient is 4.35 kV between the teflon film and the underlying ground at the poles.

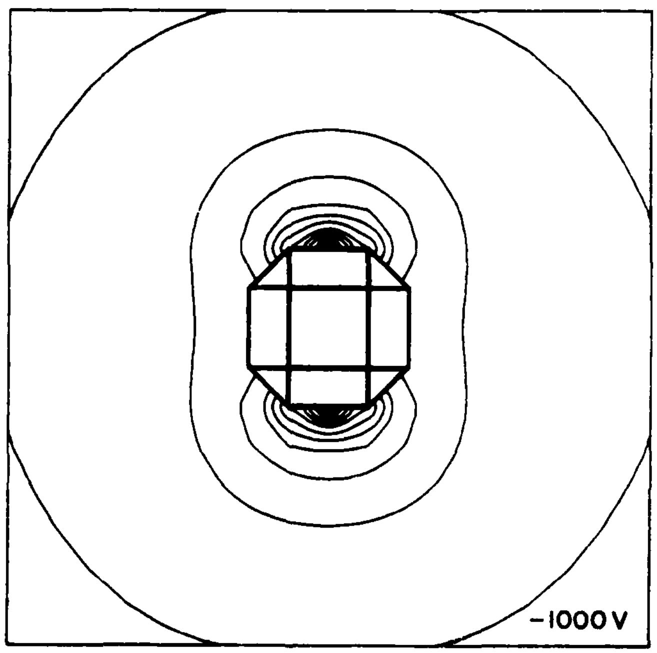

Figure 5. Steady-state Potentials on Rapidly Spinning Teflon-covered Quasisphere in Sunlight. Equipotentials are depicted at 500-V intervals. Sunlight is incident from the right. The spin axis is vertical

In summary, the effect of a rapid spin is to decrease the potentials near the satellite equator and to increase the differential potential slightly between the equator and the poles. Figure 6 shows the time development of this case starting from an uncharged state.

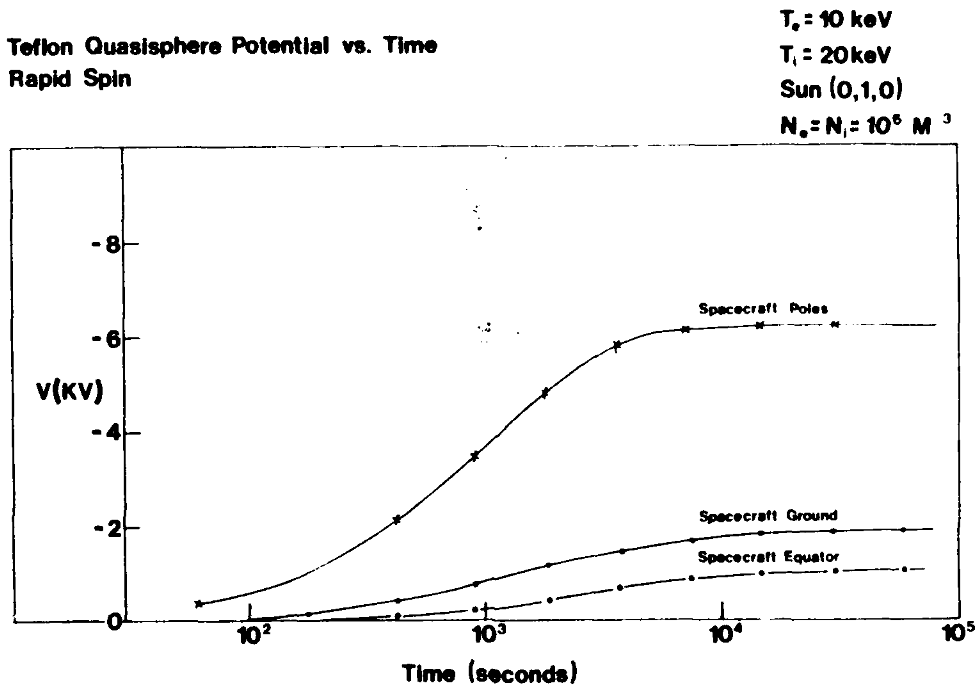

Figure 6. Time Development of Potentials on Rapidly Spinning Teflon-covered Quasisphere in Sunlight

5. CHARGING OF SLOWLY SPINNING SPACECRAFT

The spin rate of the SCATHA satellite is close to 1 revolution per minute. In order to find out whether the rapid spin approximation described above is an accurate description of this case, a series of computations was carried out. Employing the NASCAP code, potentials are calculated in the sunlit case for every 45° of rotation of the teflon quasisphere. Smaller rotation steps produce similar results as long as surface currents are negligible.

Figures 7a through 7i show the resulting potential contours. For a spin rate of 1 rpm, it is clear that the photosheath is not uniform azimuthally as in the rapid

spin case. The surface potentials in this case are much closer to the values for the rapid spin case than to the values for a non-spinning spacecraft. On the shaded side the potential at -1450 V is ~40 percent higher than in the rapid spinning case. The pole (-6500 V), sunward side (-1170 V), and ground (-2150 V) potentials are 5 to 10 percent higher than the values for the rapid spin case.

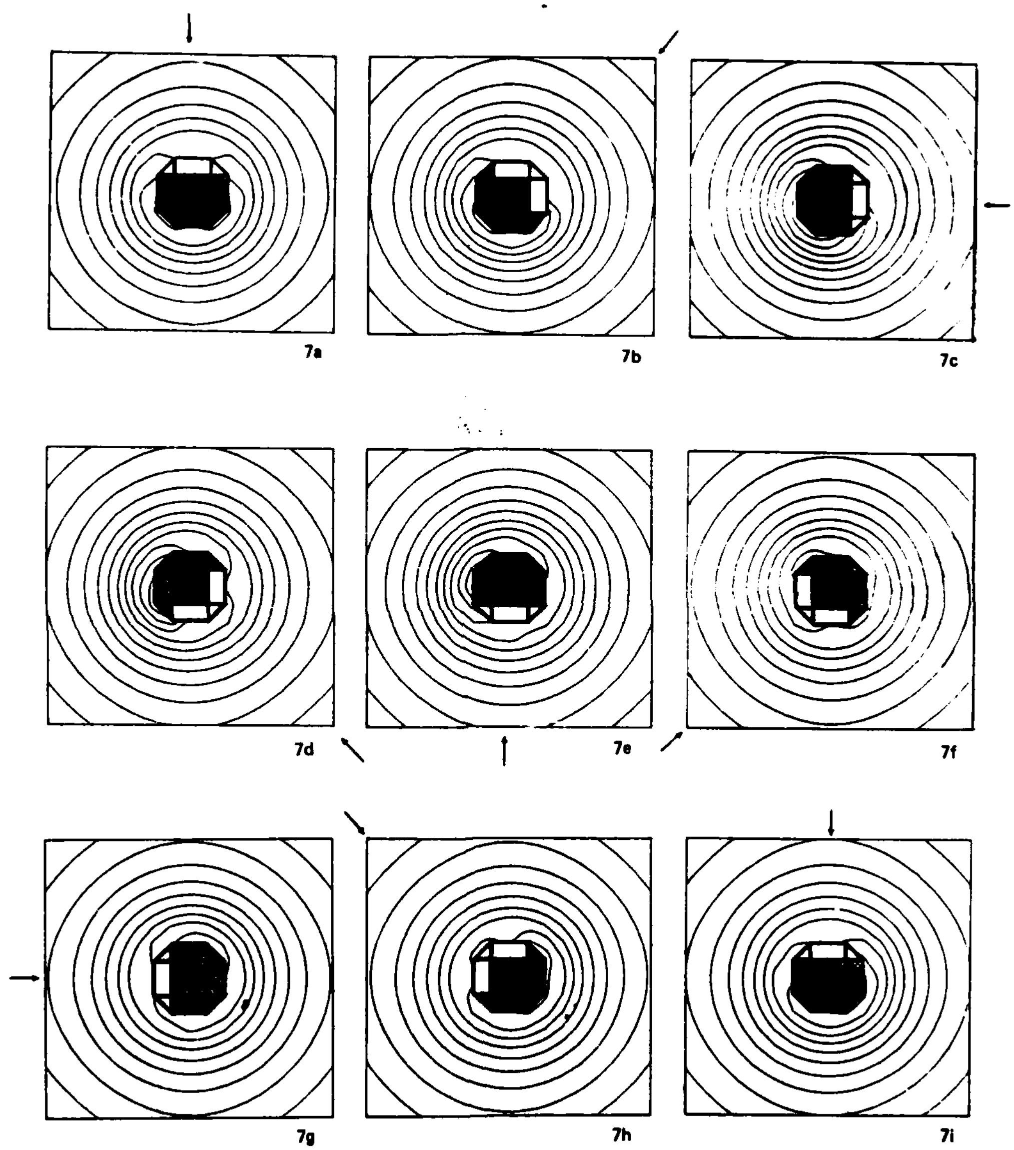

Figure 7. Potential Distribution on a Sunlit Teflon-covered Quasisphere at 1 rpm. Figures (a) through (i) show the potentials at successive 45° positions from the start. Arrows indicate sun direction. Equipotential contours are separated by 100 volts

The sun-shade peak-to-peak modulated voltage of 280 V can be readily seen to be the differential charging of the teflon layer by a shade charging flux of $\sim 1\ \mu A/m^2$ on a thin film capacitance $\sim 0.14\ \mu F/m^2$. This periodic process is sustained for somewhat more than half a revolution, followed by rapid photoemissive discharge to a level that provides current balance with the charging in the shaded polar regions. In this uniform quasisphere the ground potential is always the average of the potentials on all the surface cells around the quasisphere.

For the 1 rpm case, the potential contours still exhibit the saddle point behavior, resembling a combination of monopole and dipole components, unlike the rapid spin case in which the dipole potential averages out. In addition, comparison of Figures 7a to 7i show that a few steps after continuation from the rapid spin case, the potential contours lag the rotation and become non-symmetrical. For the 1 rpm case, the more tedious procedure of computing the potential vs rotation angle rather than using the angle-averaged sunlight may be required to determine voltage and field modulation.

6. SUMMARY AND CONCLUSIONS

Charging calculations have been carried out for a satellite model consisting of a teflon-covered quasisphere in a strong substorm. The effects of spin have been computed by considering three cases: First, a three-axis stabilized spacecraft; second, a rapidly spinning spacecraft; and third, a spacecraft rotating at 1 rpm. These results are graphically summarized in Figure 8.

The non-rotating spacecraft is the case considered by Mandell et al.[9] Here we employ more accurate values of the secondary emission coefficients so that the potential values are more realistic. The qualitative results, however, are the same. The photosheath produces a saddle point in the potential on the sunlit side. The effect of this saddle point is to limit the amount of photoelectrons which escape, thus raising the potential on the sunlit side. This model predicts substantial daylight charging potentials because of the effect of the saddle point. We may note that only a multidimensional treatment is able to show saddle point effects.

The potential distribution for the case of rapid spin is such that the shaded poles charge to a higher potential than the equator. Again, this is a multidimensional effect.

For the case of rotation at 1 rpm, the photosheath slightly lags the rotation rate of the satellite. This calculation requires both the time dependence and the three-dimensional features of the NASCAP code for an adequate description. Actual spacecraft surfaces are a mixture of dielectrics and conductors. The results obtained here are modified when an appreciable amount of conducting surface is exposed to the sunlight.

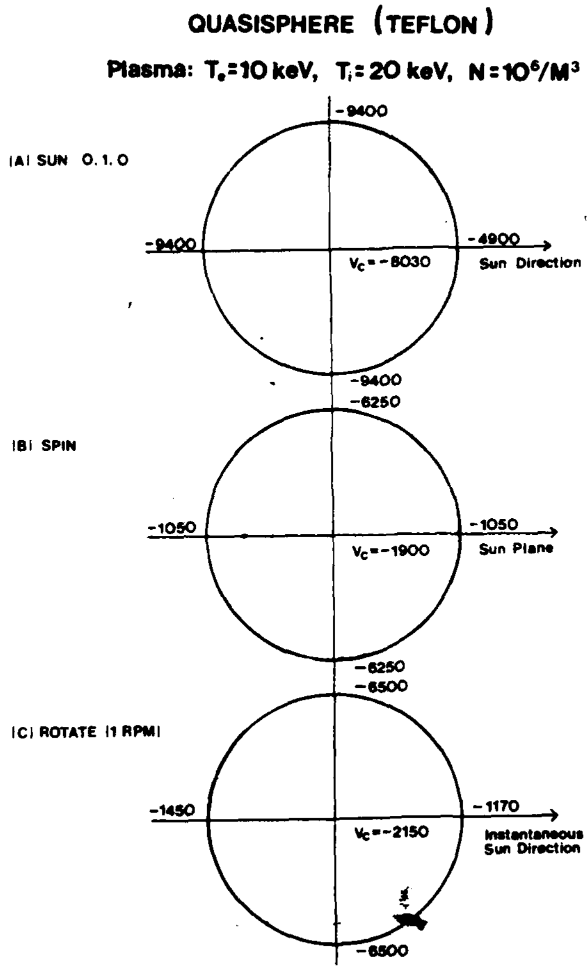

Figure 8. Comparison of the Steady-State Potentials of a Teflon-covered Quasisphere for (a) No Spin, (b) Rapid Spin, and (c) 1 rpm

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2. Spacecraft Charging by Magnetospheric Plasmas (1976) A. Rosen, Editor, MIT Press, Cambridge, Massachusetts.

3. Proceedings of the Spacecraft Charging Technology Conference (1977) C. P. Pike and R. R. Lovell, Editors, NASA TMX-75537, AFGL-TR-77-0051, AD A045459.

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